The First Year IceCube-DeepCore Results

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Abstract. The IceCube Neutrino Observatory includes a tightly spaced inner array in the deepest ice, called DeepCore, which gives access to low-energy neutrinos with a sizable surrounding cosmic ray muon veto. Designed to be sensitive to neutrinos at energies as low as 10 GeV, DeepCore will be used to study diverse physics topics with neutrino signatures, such as dark matter annihilations and atmospheric neutrino oscillations. The first year of DeepCore physics data-taking has been completed, and the first observation of atmospheric neutrino-induced cascades with IceCube and DeepCore are presented.

1. Introduction

The DeepCore extension to IceCube, shown in Fig. 1, triggers on atmospheric neutrinos at energies between about 10 GeV and 1 TeV [1, 3]. The understanding of the production and oscillations of the neutrinos at these energies is intrinsically interesting [2], not least because these neutrinos constitute an important background to astrophysical signal searches, such as neutrinos from WIMP annihilations [4] and neutrinos from soft-spectrum point sources [5].

To observe neutrinos in this energy range, DeepCore relies on compact sensor spacing, high quantum efficiency photomultiplier tubes (PMTs), deployment in the clearest ice, and a lower trigger threshold than the surrounding IceCube detector [1]. We report the DeepCore performance with 79 strings of IceCube operating (IC-79), and highlight results from the first observation of atmospheric neutrino-induced cascades in IceCube.

2. IC-79 Data

The IC-79 data collected between May 31, 2010 and May 13, 2011 have been processed and analyzed. The raw data include a series of waveforms read out from digital optical modules (DOMs) in two modes [6]. In hard local coincidence (HLC) mode, in which both the primary DOM and the nearest or next nearest neighbor DOM report a hit within a ±1000 ns time window, full waveform digitization is acquired. If a DOM is in soft local coincidence (SLC) mode without neighboring hits, a reduced waveform data is acquired consisting of the three digitization bins from the first 16 samples: the highest bin and its two neighboring bins. Therefore, hits in this paper mean DOM readouts in HLC plus SLC modes unless specified. Software is used to remove spatially and temporally isolated SLC hits due to noise. The additional SLC hit information improves event reconstruction, background rejection, and particle identification especially for low multiplicity events.

A low threshold trigger (SMT3), demanding 3 or more HLC hits within a time window of 2500 ns, is applied to DOMs in the fiducial region (the shaded area below the dust band in Fig.

1). Additionally, upgraded PMTs in the DeepCore strings with a $\sim 35\%$ increase in quantum efficiency compared to standard IceCube PMTs, help trigger on neutrinos with energies as low as 10 GeV [7].

3. Observation of Atmospheric Neutrino-induced Cascades

Atmospheric neutrinos are the decay products of charged mesons ($\pi^{\pm}$, $K^{\pm}$) produced in cosmic ray collisions with nucleons in the atmosphere. Cascades are produced by charged-current (CC) electron and tau neutrino interactions, and neutral-current (NC) neutrino interactions of any flavor, and create spherically-symmetric light distributions in ice. Although many atmospheric neutrino-induced muons, long tracks created by CC interactions, have been collected by IceCube [8], cascades have not been conclusively observed in other IceCube analyses [3, 10, 11] due to lack of a sufficient veto against the cosmic ray muons, and their low rate [9].

3.1. Background

The dominant backgrounds for the atmospheric cascades consist of cosmic ray muons that mimic signal events and ν_{μ}^{CC} events with dim tracks. In conventional atmospheric ν_{μ}^{CC} detection, muon direction information is used to reject background while a cascade analysis identifies the light pattern of the showers and enforces containment of the signal. Therefore, veto techniques with strict signal containment in DeepCore were developed to remove more than six orders of magnitude of background events while retaining reasonable signal efficiency for atmospheric neutrino-induced cascades in the fiducial volume.

3.2. Event Selection

IC-79 collected data for 348 days. Over 90% of the data are high quality and are used for physics analyses. A DeepCore on-line filter is run on the SMT3 triggered event sample at the South Pole. The pass rate is 17.5 Hz. The filtered data are sent north for subsequent processing. The filter algorithm [1] starts by calculating the center of gravity (COG) of all HLC hits in the fiducial volume to get an interaction vertex and time estimate. Then, the filter disregards any events consistent with a cosmic ray muon entering the detector volume by examining the speed between an individual HLC hit in the veto volume and the COG. A factor of 10 reduction in data compared to the triggered events are reached

Figure 1. Schematic top and side views of IceCube in its 79-string configuration. The DeepCore sub-array is defined with 6 densely deployed strings and the 7 nearby standard strings. The relative dust concentration and the DeepCore fiducial volume below the dust layer are also shown.

by this algorithm while keeping 99% atmospheric neutrinos that interact in the fiducial volume. After applying noise cleaning algorithms that remove hits which are not correlated in space and
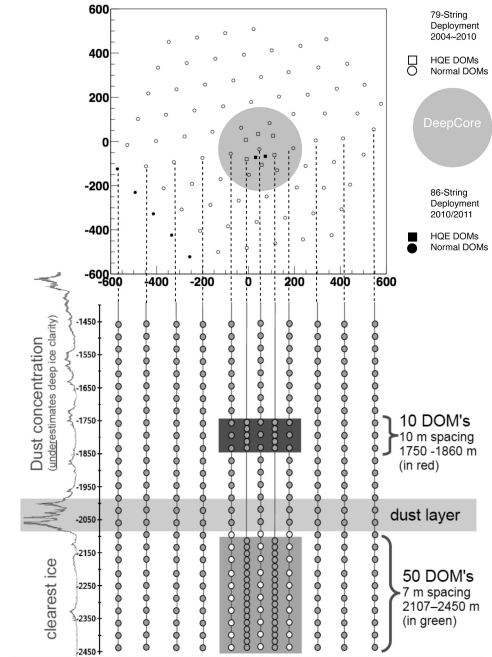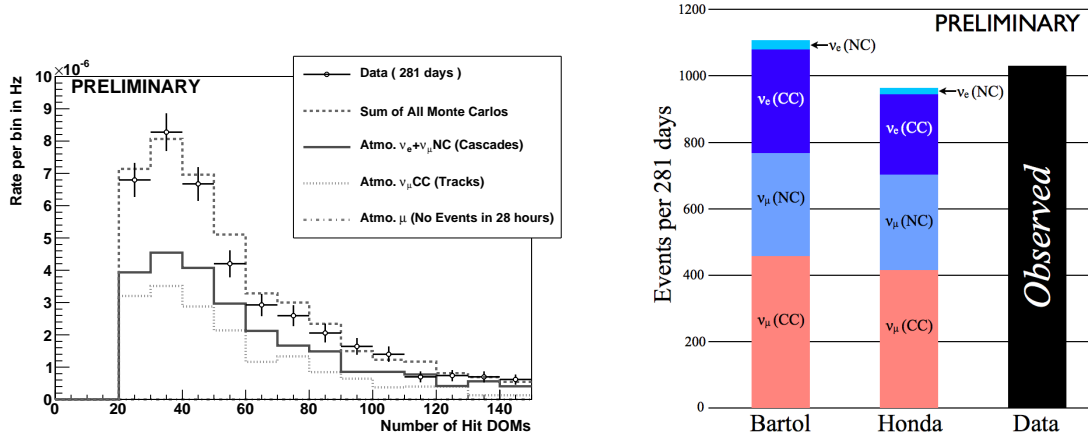
Figure 2. The left plot shows the event rate as a function of the number of hit DOMs. The sum of all Monte Carlo samples is consistent with 281 days of data rate. The cascades are expected to contribute 59% and the tracks are expected to contribute 41%. No atmospheric muon background events are left in 28 hours of simulated data. The oscillation effect is less than 3% at these energies and is neglected here. The bar histogram on the right indicates MC contributions from different interactions with two atmospheric flux models (Bartol [14] and Honda [15]) and the observed data rate. Errors are statistical only.

time with other hits, events with at least 8 total remaining hits and at least 4 hits in the fiducial region are selected.

The next background rejection is performed by a machine learning technique with a Boosted Decision Tree (BDT) [12]. The "BDT5" is formed from five observables which are constructed from the spherical hit pattern, localized time structure, and quick charge deposition, identifying cascade shapes in the detector. The BDT5 selection reduces the data rate to 0.1 Hz, achieving a factor of almost 1800 reduction with respect to the trigger. The atmospheric ν_e rate is predicted to be 6.2×10^{-4} Hz (about 180 times lower than data rate), corresponding to 63% retention with respect to the trigger.

The reduced data set was then processed with iterative likelihood reconstructions taking into account detailed Cherenkov light propagation in the ice [13]. Hits falling outside the time window [-3000 ns, +2000 ns] with respect to the trigger, or outside of a 150 m radius of a neighboring hit within a 750 ns time window, are removed. Then, with the remaining hits, after demanding 8 or more hits in the fiducial region within a 1000 ns sliding window, another BDT is formed with 7 input parameters (BDT7). Two variables measure the locations of the earliest hits in terms of radial and vertical coordinates to select contained events. The next three variables separate cascade-like events from muon-like events; an event is split in half and then charge deposition, COG, and particle speed are compared between the two separate halves. The remaining two variables compare likelihoods of a cascade hypothesis to that of a muon hypothesis. The BDT7 selection reduces the atmospheric muon background to 5.0×10^{-4} Hz by rejecting a factor of 200 more (3.6×10^5 cumulatively) background while retaining ~40% of the ν_e signal (2.6×10^{-4} Hz) compared to the previous BDT5 cut.

3.3. Results
A set of tight cuts is made on the previously selected BDT7 sample which contains a large fraction of atmospheric neutrinos. The cuts aim for high purity cascade detection by rejecting as many

Type	ν_e^{NC}	ν_e^{CC}	ν_μ^{NC}	ν_μ^{CC}	MC Sum	$\mathrm{N^{obs}}$
	$\mathrm{C^{sig}}$			$\mathrm{C^{bg}}$		
Bartol	25	312	314	455	1106	-
Honda	18	245	287	415	965	-
Data	-	-	-	-	-	1029

Table 1. The number of events are shown with final selections. $\mathrm{N^{obs}}$ means observed events in 281 days of real data. $\mathrm{C^{sig}}$ and $\mathrm{C^{bg}}$ refer predictions of the cascade signal and its background respectively. The MC numbers use 281 days normalization and their statistical errors are $\sim 3\%$.

ν_μ^{CC} events as possible. Containment cuts based on the vertex depth measurements ensure that most signal events are well contained inside the DeepCore fiducial volume. They select a volume smaller than the nominal DeepCore fiducial volume to identify an outgoing track from a ν_μ^{CC} interaction. Reconstruction quality cuts select events that fit a cascade hypothesis better, as measured by the log likelihood from a fit. Additionally, the selection includes a stronger cut on the BDT7 parameter and a requirement of ≥ 20 hit DOMs to remove the remaining cosmic ray muon background. As shown in Figure 2, with 281 days of data, we observe 1029 total events and expect 651 cascades and 455 tracks from simulation using the Bartol atmospheric neutrino flux model [14]. A lower rate prediction from the Honda model [15] due to a different treatment of kaon production in the atmosphere [9, 16] is presented in the right histogram of Fig. 2 and in Table 1. The remaining simulated ν_μ^{CC} events have short muons with a median track length of 80 m where the muon tracks are not detected by this analysis. About 50% of the cascades are predicted to be ν_e events and the balance ν_μ^{NC} events. The mean cascade energy is 180 GeV, high enough that $\nu_\mu \to \nu_x$ oscillations has a small ($<3\%$) effect. The atmospheric muon simulation predicts zero events in 28 hours. Systematic errors are not included.

4. Conclusion
We report on the first observation of atmospheric neutrino-induced cascade events with IceCube and DeepCore. The preliminary summary of the results is shown in Table 1. Systematic errors originating from ice modeling, detection efficiency of DOMs, neutrino-nucleon cross-sections, and atmospheric neutrino flux model are under evaluation. In the near future, data analyses using a similar technique as that presented here, focusing on neutrino oscillations, WIMP searches, and neutrino surveys for the southern sky, are expected.

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